



Simulations of radiation pressure ion acceleration with the VEGA Petawatt laser



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ABSTRACT

The Spanish Pulsed Laser Centre (CLPU) is a new high-power laser facility for users. Its main system, VEGA, is a CPA Ti:Sapphire laser which, in its final phase, will be able to reach Petawatt peak powers in pulses of 30 fs with a pulse contrast of $1 : 10^{10}$ at 1 ps. The extremely low level of pre-pulse intensity makes this system ideally suited for studying the laser interaction with ultrathin targets. We have used the particle-in-cell (PIC) code OSIRIS to carry out 2D simulations of the acceleration of ions from ultrathin solid targets under the unique conditions provided by VEGA, with laser intensities up to $10^{22} \text{ W cm}^{-2}$ impinging normally on 20–60 nm thick overdense plasmas, with different polarizations and pre-plasma scale lengths. We show how signatures of the radiation pressure-dominated regime, such as layer compression and bunch formation, are only present with circular polarization. By passively shaping the density gradient of the plasma, we demonstrate an enhancement in peak energy up to tens of MeV and monoenergetic features. On the contrary linear polarization at the same intensity level causes the target to blow up, resulting in much lower energies and broader spectra. One limiting factor of Radiation Pressure Acceleration is the development of Rayleigh–Taylor like instabilities at the interface of the plasma and photon fluid. This results in the formation of bubbles in the spatial profile of laser-accelerated proton beams. These structures were previously evidenced both experimentally and theoretically. We have performed 2D simulations to characterize this bubble-like structure and report on the dependency on laser and target parameters.

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1. Introduction

The acceleration of ions via laser–plasma interactions has been studied extensively in recent years. The strong electric fields present during high-intensity laser–matter interaction enable the production of MeV-ion beams, that can potentially be used for a wide range of applications, including hadron therapy, fast ignition and proton radiography [1,2]. Besides Target Normal Sheath Acceleration (TNSA) [3,4], in which protons are accelerated through a large charge-separation field at the rear side of an overdense plasma, other promising mechanisms have emerged. Radiation Pressure Acceleration (RPA) [5], based on the momentum transfer from photons to electrons, offers a much better scaling and produces ions with tens of MeV energy. Other schemes at the onset of relativistically induced transparency [6] like the

Breakout Afterburner (BOA) [7,8], where the interaction changes from surface-dominated to volumetric, have also emerged.

The RPA mechanism is one of the most promising candidates for the efficient acceleration of mono-energetic ion beams. Two distinct regimes of RPA have been identified, namely Hole Boring and Light Sailing. Hole Boring acceleration, sometimes also referred to as collisionless shock acceleration [9] dominates for thicker targets in the micrometer range. The plasma is pushed inwards by the light pressure, piling up electrons and forming an electron density spike in front of the laser pulse. This generates strong charge separation fields and the ions are pulled forward to high energies [1].

For thinner targets, Light Sailing acceleration becomes accessible. In this case the radiation pressure drives and compresses the electrons out of the target, thereby setting up an ultra-high charge separation field. This field accelerates the ions rapidly and the accelerated plasma slab can be considered as a relativistically moving mirror co-propagating with the laser pulse (Light sailing); the energy is transferred to the electrons by momentum transfer

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of the reflected and down-shifted laser. In the final acceleration phase and under optimum conditions, the ions are traveling with nearly the same velocity as the electrons, giving rise to high-energy ion beams [5].

Both light-sailing RPA and BOA dominate for ultrathin overdense targets in the range of nanometres. Such targets require delicate handling and an ultrahigh contrast to prevent destruction by the pre-pulse [10]. Usually a plasma mirror system is used to enhance the contrast, but this reduces the laser energy throughput significantly.

The VEGA Petawatt system at CLPU will produce intense laser pulses with a pulse contrast of $1 : 10^{10}$ at 1 ps. This will allow the experimental study of laser-matter interaction with ultrathin solid targets without the use of a plasma mirror and therefore gives the opportunity to study laser-matter interaction at highest achievable intensities. Laser-driven ion acceleration has been explored for this set-up using fully relativistic 2D particle-in-cell simulations.

2. Methodology

The simulations have been performed with the fully relativistic particle-in-cell (PIC) code OSIRIS [11] on a grid of 39133×168 cells in a box of $20 \times 29 \mu\text{m}$ size. Each cell initially contains 1000 particles and they are pushed with a time step of 1.68×10^{-18} s. The laser pulse has a \sin^2 pulse envelope with a duration of 40 fs FWHM and is focused to a diameter of $5 \mu\text{m}$. Diamond-like carbon (DLC) is chosen as a target material. The target is assumed to be fully ionized by the prepulse accompanying the main pulse and modeled as a plane slab of plasma with a step density profile of $n_e = 460 n_{cr}$, where n_{cr} is the critical plasma density. The initial electron temperature is set to 1 keV, while ions are assumed to be cold. All simulations are performed with a realistic carbon mass to charge ratio $m_c/q_c = 3645$. The laser always impinges normally onto the plasma slab. The energies in the figures have been extracted according to $E_i = (\gamma - 1)m_i c^2$, where γ is the relativistic factor of the ions.

3. Simulations from ultrathin solid targets

A number of parameter scans have been carried out to find the optimum conditions for the most efficient laser-driven ion acceleration from ultrathin solid targets with the VEGA laser system. Signatures of the radiation pressure-dominated regime such as electron and ion layer compression and ion bunch formation in the density profile, are observed in the irradiation of ultrathin targets with circular polarization. Fig. 1 shows the moving carbon ion front with time for a range of different laser and target parameters. Clearly an initial acceleration phase (ramp-up) can be identified, which has an approximate length of the laser pulse duration. After this rapid acceleration, the ion front moves with constant velocity suggesting no further post-acceleration mechanisms. The maximum ion energy has a steeper scaling with intensity than observed in TNSA [12] and also depends sensitively on the target thickness. The highest ion cut-off energies are obtained with the thinnest targets, where the areal density is closer to the optimum $\sigma_{opt} \approx a_0/\pi$ as predicted by Macchi et al. [13]. Circular polarization suppresses electron heating efficiently and compresses the target up to ten times the initial density. In contrast, a linearly polarized laser pulse with the same intensity causes the target to blow up at an early stage of the interaction, resulting in a very low flux of particles and a much broader energy spectra. We have also performed a set of simulations with proton targets, which produce more energetic particle energies than the carbon targets under otherwise identical conditions. To model the laser-matter

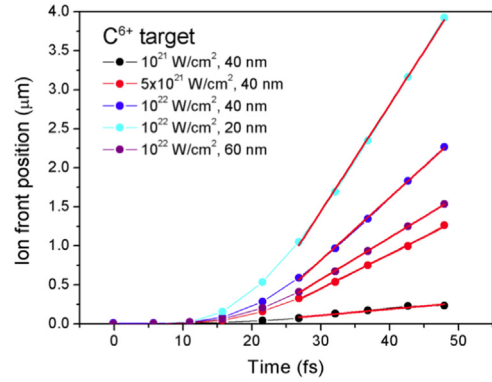


Fig. 1. Carbon ion density front moving in time. After an initial acceleration phase, the carbon ions move with constant velocity suggesting no further post-acceleration.

interaction under realistic conditions, we have also produced a simulation with a double layer, i.e. a carbon target with a hydro-contamination layer. Both carbon ions and protons propagate at the same speed. The similarity of the maximum energies per nucleon observed in the spectra for both species, suggests an efficient co-acceleration.

3.1. Influence of laser intensity

We have performed a set of simulations with 40 nm targets with the aforementioned parameters (circular polarization) and varied the intensity between $10^{21} \text{ W cm}^{-2}$ and $10^{22} \text{ W cm}^{-2}$. As it can be seen in Fig. 2, a change in intensity strongly modulates the ion spectra and cut-off energies. Doubling of the laser intensity results in a four-fold increase in cut-off energy when comparing $5 \times 10^{21} \text{ W cm}^{-2}$ with $10^{22} \text{ W cm}^{-2}$. The electron and carbon layers are efficiently compressed and the ion spectra shows a strong mono-energetic peak near the cut-off energy.

3.2. Influence of target thickness

The highest energies are obtained for the thinnest target, where the areal density is closer to the optimum $\sigma_{opt} \approx a_0/\pi$ as predicted by Macchi et al. [13]. The spectrum for the 20 nm target has a slightly fractured shape and features a number of peaks at the high-energy end of the spectrum. This can be caused by the development of instabilities that are formed throughout the interaction as will be discussed in Section 3.4. The cut-off energies seem to scale almost linearly with decreasing target thickness as observed in Fig. 2.

3.3. Influence of laser polarization

It has been shown that the effectiveness of the RPA mechanisms is highly dependent on the polarization of the laser pulse [14]. A linearly polarized (LP) laser pulse heats the plasma more efficiently, thereby causing the target to blow up at an early stage of the interaction. Although the simulation (Fig. 3) shows fairly high cut-off energies, it follows a rather thermal distribution with no sharp peaks and the number of these high-energy particles is negligible. While linearly polarized pulses are not well-suited for ion acceleration in the nano-scale RPA regime, other emerging mechanisms including TNSA, BOA [8] and relativistically induced transparency acceleration [6] can occur. The collective charged particle dynamics in these interactions also depend highly on target thickness and have been studied experimentally and theoretically [15,16]. It has been shown theoretically that Radiation Pressure Acceleration is most effective with a circularly polarized

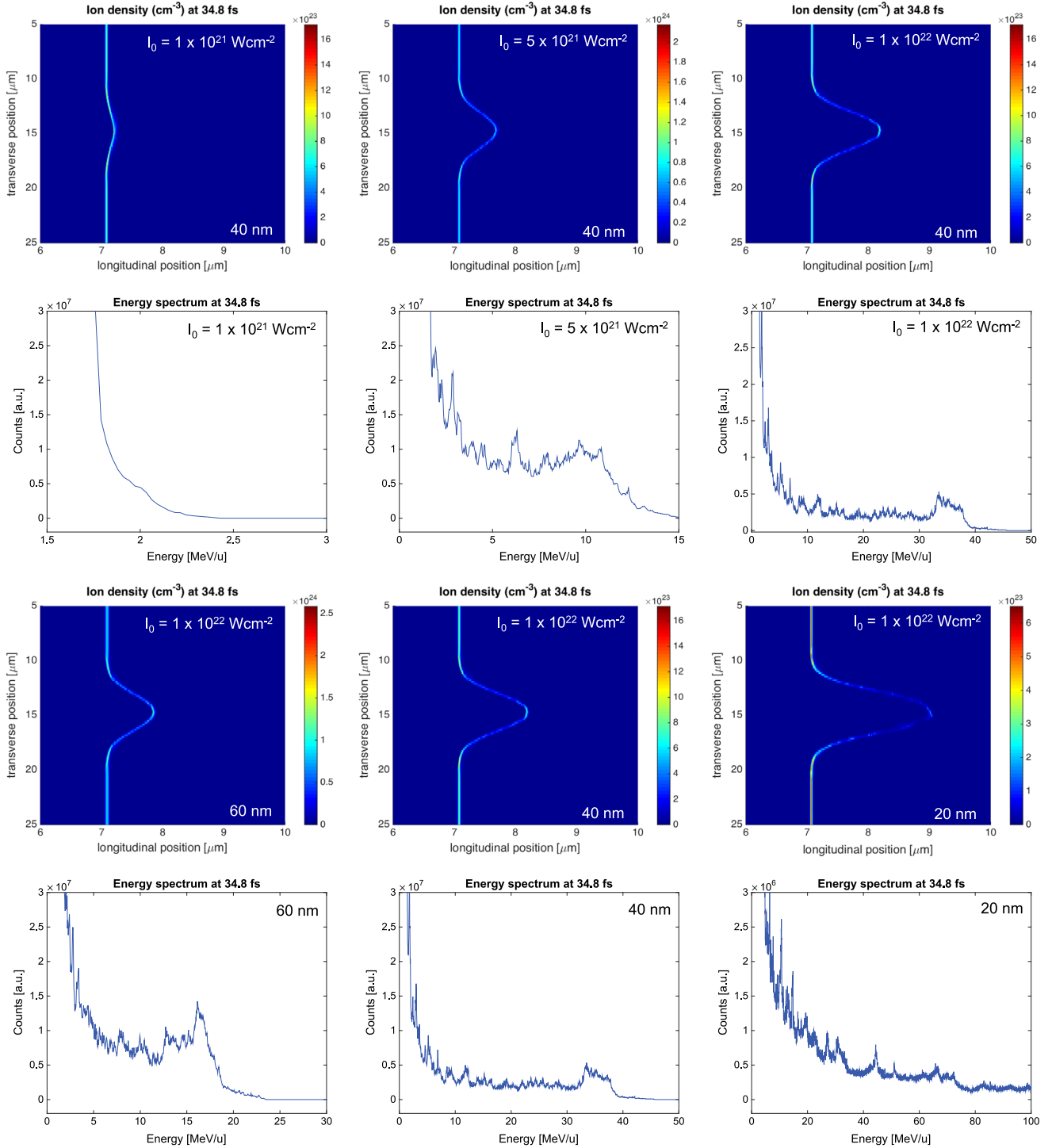


Fig. 2. Intensity scan for 40 nm carbon targets (left column) and thickness scan for $10^{22} \text{ W cm}^{-2}$ (right column) under otherwise identical conditions (see text for details). The charge densities and ion spectra are shown. The time corresponds to the time after the laser pulse impinges on the target. The cut-off energies increase significantly with increasing intensity. Also, the highest energies are observed with decreasing target thickness and ion spectra shows stronger modulations for the thinnest target. The light blue color in the bunch corresponds to high densities, whereas the purple color indicates low density regions. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

(CP) laser pulse [14]. The circular polarization suppresses electron heating as the oscillating part of the ponderomotive force is absent. A fast oscillating component would lead to electrons being strongly heated and leaving the interaction area after a few laser cycles as in TNSA. Instead, in the case of circular polarization, the ponderomotive force is slowly varying and electrons are adiabatically compressed. Fig. 3 shows that in the CP case, the bunch compression of the ions and electrons is very efficient and the

spectrum features a distinct mono-energetic peak at around 35 MeV/u.

3.4. Rayleigh–Taylor instabilities

The ion beams generated in the RPA regime are prone to transverse instabilities, which have been attributed to Rayleigh–Taylor instability-types previously [17] and have been observed theoretically

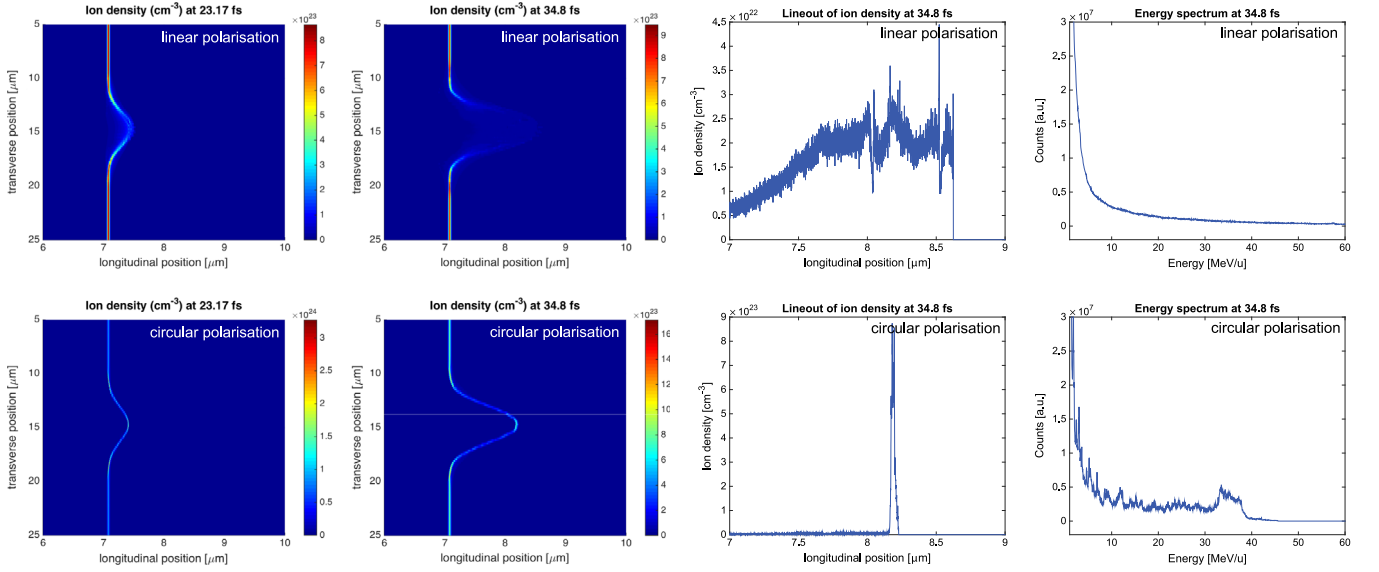


Fig. 3. Linear and circular polarization comparison for carbon targets under otherwise identical conditions ($I = 10^{22} \text{ W cm}^{-2}$, 40 nm thick target. See text for details). The charge densities, line-outs of the charge density and ion spectra are shown. The time corresponds to the time after the laser pulse impinges on the target. The linearly polarized laser pulse strongly heats the plasma electrons and drives target expansion to near-critical density values. While high cut-off energies are reached, the spectrum has a thermal shape with no sharp peaks. The circularly polarized pulse efficiently pushes the plasma inwards and drives a compressed ion bunch to high energies.

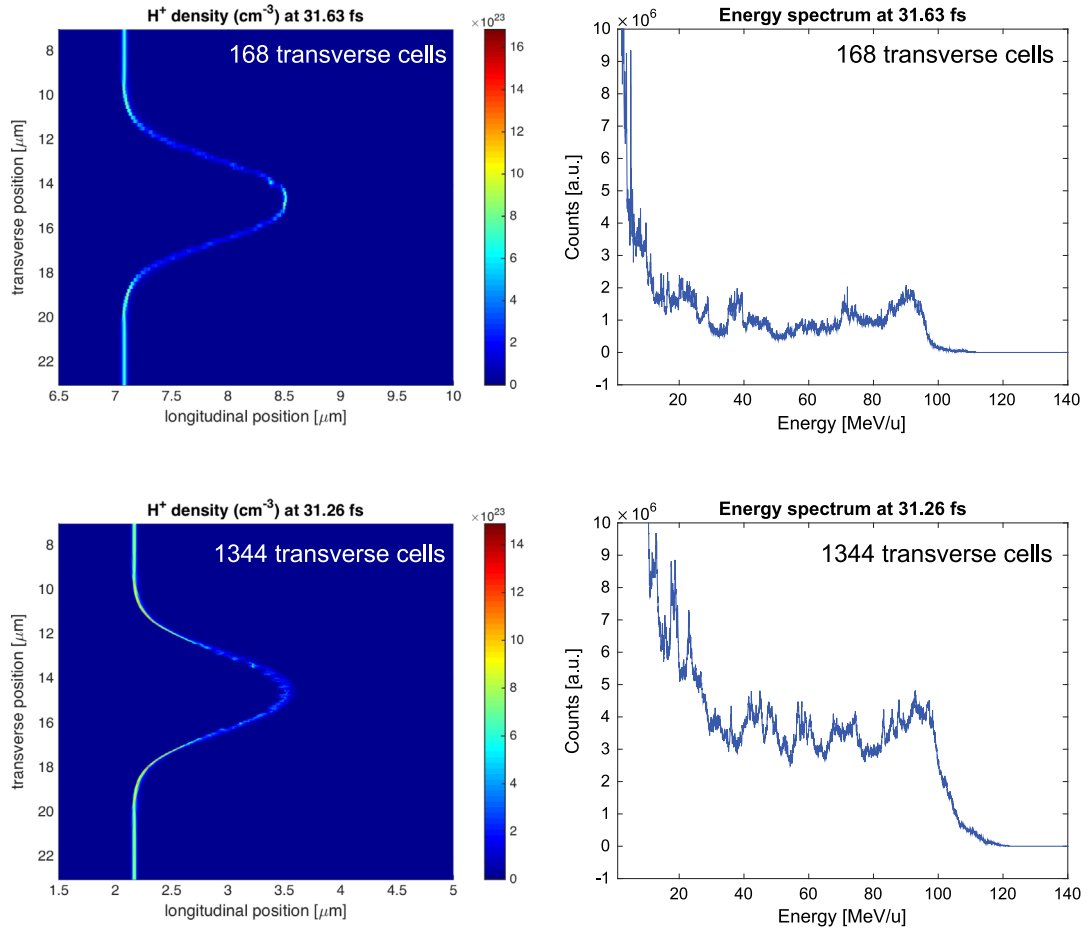


Fig. 4. Comparison of a lower and higher resolution simulation run. The target consists of H^+ , otherwise simulation parameters are identical to the second run in Fig. 2. The high resolution run has an eight-fold increase in cells in the transverse direction. This reveals in more detail the development of the instabilities. Note that there are more particles in the higher resolution simulation run (particles per cell same as in lower resolution simulation). This causes a higher yield in particle numbers.

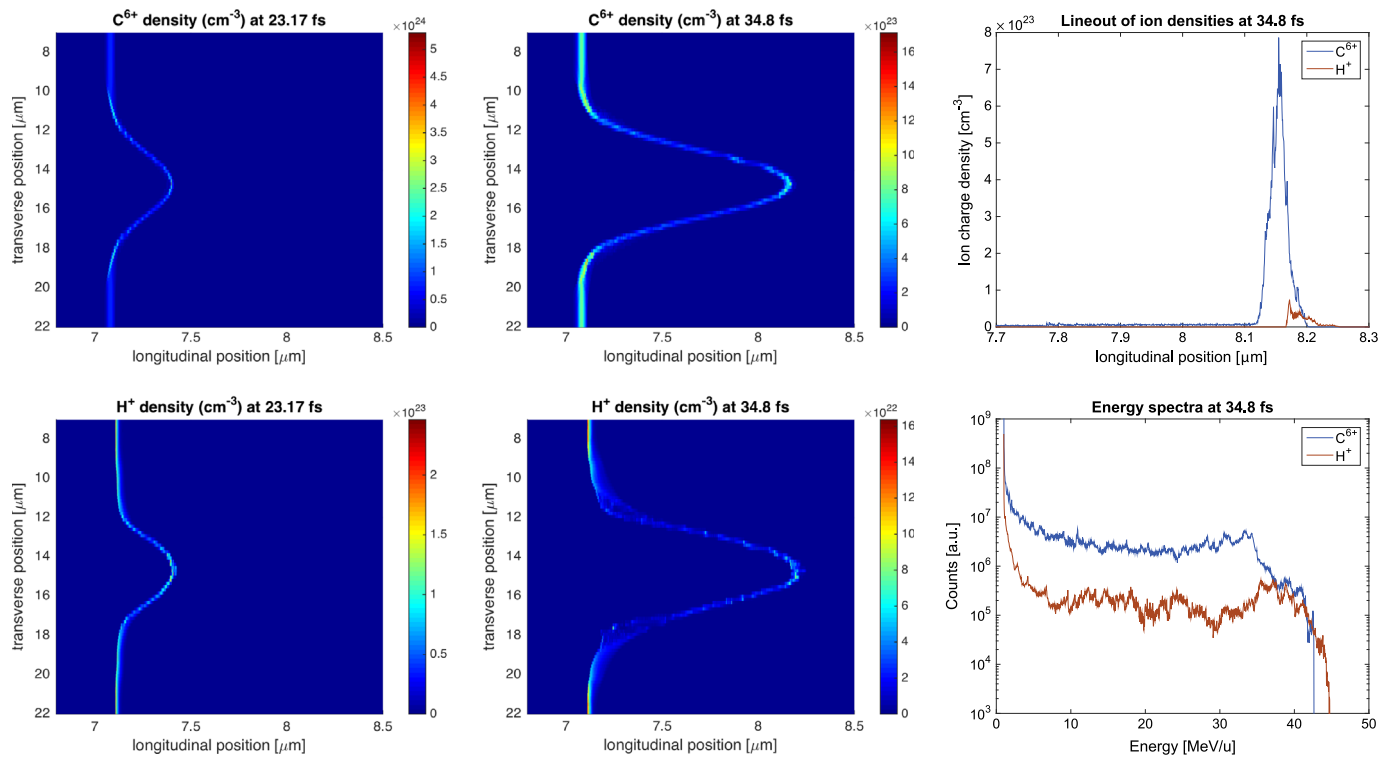


Fig. 5. Interaction of a laser pulse with a 40 nm carbon target with a 5 nm hydrogen contamination layer. The simulation parameters are otherwise identical to the second run in Fig. 2. The similarity in spectral features suggests an efficient acceleration of both ion species. Note that the y-axis of the energy spectrum is displayed with a logarithmic scale to facilitate comparison between both species.

and experimentally [18]. The Rayleigh–Taylor instability can be seen as a result of a light fluid (photons) pushing into a heavier fluid (plasma). At the interface of these fluids, perturbations can grow in the form of bubbles when the low density fluid penetrates into the high density fluid. In order to study the development of transverse instabilities, we have performed a comparison simulation with an eight-fold increase in number of cells in the transverse direction. While the overall dynamics is in principle maintained, it can be seen that the charge density in the wings stays overdense, whereas for the lower resolution runs it approaches near-critical values quicker. The higher resolution run amplifies the modulation in the spectral shape as it can be seen in Fig. 4.

3.5. Multi-layer target

Fig. 5 shows the interaction of a circularly polarized laser pulse with a 40 nm carbon target with a thin, 5 nm, hydrogen contamination layer. In this case, the carbon layer is compressed, and both carbon ions and protons propagate at the same speed. The similarity of the maximum energies per nucleon observed in the spectra for both species suggests an efficient co-acceleration in the RPA regime.

The interaction of a linearly polarized laser pulse would strongly heat the bulk electrons, causing the formation of a strong sheath field at the rear side of the target like in the TNSA mechanism. This would result in a preferred acceleration of the hydro-contaminants, i.e. protons, diminishing the effectiveness of the RPA mechanism for heavier ions.

4. Summary

We simulated the production of high-energy ion beams from ultra-thin solid targets with the VEGA Petawatt laser. Due to its high contrast, VEGA is very suitable to accelerate ions in the

Radiation Pressure regime utilizing ultrathin solid targets. We have shown that the spectral shape of the produced ion beam is strongly dependent on both laser and target parameters. The highest energies are obtained with the thinnest targets, circular polarization and the highest intensities, all of which are achievable by the VEGA system. Under these conditions, the RPA regime is accessible and we have shown the production of up to 100 MeV/u carbon ions. However an increased transverse resolution further reveals the development of Rayleigh–Taylor type instabilities, which modulate the spectral shape of the ions and impede the production of true monoenergetic ion beams.

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